STELLAR VARIABILITY AND ITS IMPLICATIONS FOR PHOTOMETRIC PLANET DETECTION WITH *KEPLER*

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Abstract

Kepler is one of three candidates for the next NASA Discovery Mission and will survey the extended solar neighborhood to detect and characterize hundreds of terrestrial (and larger) planets in or near the habitable zone. Its strength lies in its ability to detect large numbers of Earth-sized planets – planets which produce a 10^{-4} change in relative stellar brightness during a transit across the disk of a sun-like parent star. Such a detection requires high instrumental relative precision and is facilitated by observing stars which are photometrically quiet on hourly timescales. Probing stellar variability across the HR diagram, one finds that many of the photometrically quietest stars are the F and G dwarfs. The Hipparcos photometric database shows the lowest photometric variances among stars of this spectral class. Our own Sun is a prime example with RMS variations over a few rotational cycles of typically $3-4\times10^{-4}$ (computed from VIRGO/DIARAD data taken Jan-Mar 2001). And variability on the hourly time scales crucial for planet detection is significantly smaller: just $2-5\times10^{-5}$. This bodes well for planet detection programs such as *Kepler* and *Eddington*. With significant numbers of photometrically quiet solar-type stars, Earth-sized planets should be readily identified provided they are abundant in the solar neighborhood. In support of the *Kepler* science objectives, we have initiated a study of stellar variability and its implications for planet detection. Herein, we summarize existing observational and theoretical work with the objective of determining the percentage of stars in the *Kepler* field of view expected to be photometrically stable at a level which allows for Earth-sized planet detection.

Key words: Stars: activity – Planets: exoplanets

1. Introduction

Kepler (Borucki et al. 1997) is one of three candidates for the next NASA Discovery Mission. It proposes to survey the extended solar neighborhood to detect and characterize hundreds of terrestrial (and larger) planets in or near the habitable zones of solar-type stars. It is designed to photometrically monitor more than 100,000 main sequence stars continuously over a period of at least 4 years with a relative precision of 2×10^{-5} on 2 to 16 hour timescales. Its relatively large aperture ($\sim$ 1 meter) and wide field of view ($\sim$ 105 square degrees) make this possible.

Planets will be identified by observing the repeating drops in stellar brightness ($\delta F/F \leq 0.02$) which occur each time a planet (whose orbit lies very nearly along *Kepler's* line of sight) transits the disk of its parent star. In November, 1999, exactly such an event was reported: a short-period (3.5 day), Jupiter-sized ($>0.62M_{Jup}$) planet in an eclipsing orbit about HD 209458 (G0V) produced an $\sim$ 2% decrease in the system brightness (Henry et al. 1999; Latham et al. 1999). Though this planet was first detected by Doppler velocity techniques, the event well-illustrates the utility of this photometric technique as a tool for planet detection in edge-on, eclipsing systems. The strength of the *Kepler* mission lies in its ability to detect large numbers of Earth-sized planets which is not currently feasible from any ground or space-based platform.

If we could watch the Earth transit the solar disk with sufficiently keen eyes from a vantage point outside the solar system, we would observe a fractional change in the solar brightness of only 8×10^{-5} lasting approximately 13 hours. Careful engineering and a large telescope aperture reduce instrument noise and Poisson noise down to acceptable levels for the detection of such a low-level signal. Putting the instruments in space eliminates scintillation noise. And rigorous testing of CCD's assures us that the stringent signal to noise requirements can be met (Robinson et al. 1995). What might remain, however, is noise intrinsic to the parent star: stellar variability.

Probing stellar variability across the HR diagram, one finds that many of the photometrically quietest stars are the F and G dwarfs. The Hipparcos photometric database shows the lowest variances among stars of this spectral class (Eyer & Grenon 1997). Our own Sun is a prime example with RMS variations over a few rotational cycles of typically 2×10^{-4} (computed from VIRGO/DIARAD). And variability on the 3-16 hour time scales crucial for planet detection is significantly smaller: just 1×10^{-5}. However, the Sun is by no means constant. Figure 1 shows a composite of irradiance data taken since 1975 from various space-based radiometers (Fröhlich & Lean 1998). Both the long-term variability characteristic of the 11-year solar

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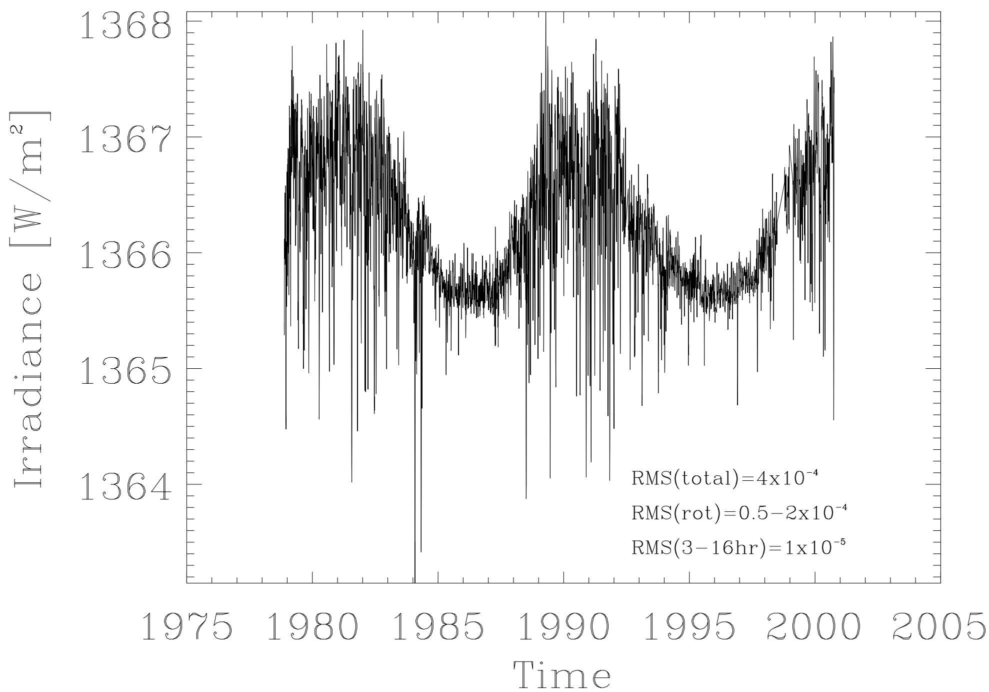

Figure 1. A composite of solar irradiance data taken from various space-based platforms since 1975 and compiled by Fröhlich & Lean (1998). Listed in the lower right-hand corner is: 1) the total standard deviation (relative) of the composite data, RMS(tot); 2) the standard deviation of the filtered composite data where only frequencies corresponding to the solar rotation timescale (25-30 days) are preserved, RMS(rot); and 3) the standard deviation of the filtered SOHO/DIARAD data where all frequencies but those corresponding to the 3-16-hour timescale are filtered out, RMS(3-16hr). The rotational RMS varies over the solar cycle. Composite data was obtained from PMOD/WRC, Davos, Switzerland.

cycle and short-term variability characteristic of the solar rotation are readily apparent in this figure.

Indeed, even the quietest stars are variable at the low levels required for detection of a terrestrial-sized planet. For the Sun and all of its main sequence counterparts (F2-K7 V stars), this variability is driven by a magnetic dynamo induced by internal convection and rotation. The solar dynamo generates a carpet of localized magnetic fields producing the well-known spots, faculae, and plages collectively known as active regions. When seen in white light images, such features appear darker (as is the case for spots) or brighter (as is the case for faculae) relative to the surrounding solar photosphere. These brightness inhomogeneities typically live for weeks to months, in which time they are carried across the solar disk by rotation. Rotating in and out of view, active regions generate variations in the integrated solar flux. The RMS variability on rotational time scales increases during solar maximum. Also characteristic of solar maximum is the increase in the mean brightness level due to the faculae whose relative brightness more than make up for the deficit produced by dark spots (on average).

Herein, we discuss the implications magnetic variability has for planet detection via photometric transit techniques. Our aim is to establish the detectability of an Earth-sized transit in the solar noise environment and to determine the percentage of stars which are expected to have sufficiently small photometric variances on the timescales of interest to planet detection.

2. Solar Variability

We have quantified solar variability at the requisite time scales (13 hours) using observations from the Active Cavity Radiometer for Irradiance Monitoring (ACRIM 1) onboard the SMM satellite. This instrument measured the total solar flux over a 4.5-year period (Willson et al 1981) from 1985 (near solar minimum) into 1989 (near solar maximum). These results have been validated by comparing them with recently-released measurements made over a 5.2-year period (beginning at solar minimum and extending well into solar maximum) beginning in 1996 by DIARAD aboard the Solar and Heliospheric Observatory (SOHO) (Fröhlich et al. 1997).

Figure 2 shows the power spectrum of the DIARAD data set along with the power spectra for 5-hour and 13-hour transits. Fortunately, there is little power due to solar variability at time scales comparable to transits (0.8 to 8 day^{-1}, or 3 to 30 hours). Most power in the measurement noise occurs at frequencies less than 0.1 day^{-1} ($>$ 10 days), corresponding to the rotation of sunspot groups and solar-cycle scale variations (Fröhlich 1987). At frequencies of 0.8 to 8 day^{-1}, the power spectrum is thought to be dominated by convection-induced processes such as granulation and supergranulation (Rabello Soares et al 1997, Andersen et al 2000). It has also been suggested that facular regions (diffuse magnetic flux producing bright filamentary structure) contribute to the power at these frequencies – frequencies corresponding to the time for passage across the solar limb where faculae have significantly higher contrast against the photosphere (Fligge et al. 2000). However, comparing the power spectrum of the SOHO data taken at solar minimum with that taken at solar maximum (Figure 2) reveals no statistically significant change in amplitude in the 0.8 to 8 day^{-1} range. This would be expected if facular regions contribute significantly to the power.

For modeling purposes we add the SOHO/DIARAD data to additional white gaussian noise representing *Kepler's* expected shot noise and instrumental noise for a $m_V = 12$ star. We inject transits into the data to generate detection statistics for Earth-sized events. A full statistical description of the detection algorithms employed will be presented in another communication (Jenkins et al., in preparation). For 13-hour transits, the mean SNR is $\sim 5\sigma$, well above the requirement of 3.5σ for a minimal detection rate of 50%. We conclude that the detection of an Earth twin around a solar twin at $m_V \sim 12$ is feasible with the Kepler platform.

3. Solar-Type Stars

Certainly not all stars behave like the Sun. The pertinent question, however, is: how typical is the Sun among its main sequence counterparts? The answer seems to depend on what type of observations we gather.

Stellar activity diagnostics (namely, the CaII H&K chromospheric emission line fluxes) of approximately 100 stars have been monitored consistently since the mid-1960's as part of the Mt. Wilson HK survey (Wilson 1978; Baliunas et al. 1995). The primary objective of this survey is to search for long-term activity cycles in solar-type stars. Vaughan & Preston (1980), also using the Mt. Wilson instruments, present single measurements for 486 solar-type stars within 25 pc of the Sun. Soderblom (1985) calibrates the Vaughan-Preston measurements (to yield the purely chromospheric emission excess as a fraction of the stellar bolometric luminosity, R'_{HK}). Henry et al. (1996) extend the sample, adding 800 southern hemisphere stars within 50 pc. Figure 7 of Henry et al. summarizes the results. Approximately 63% of the sample is classified as inactive, the Sun among them. In this sample, the Sun appears to be a typical, inactive, G-type main sequence star. Radick et al. (1998) compute the RMS variations ($\sigma_{R_{HK}}$) of a sub-sample of the Mt. Wilson targets and finds that the solar RMS is typical of stars of similar activity level ($< R_{HK} >$).

We might expect the white-light, photospheric irradiance variations to yield similar statistics. Regions of concentrated magnetic flux in the solar chromosphere (plages) are bright in the CaII lines relative to the surrounding chromosphere and are physically associated with the dark spots of the underlying photosphere. However, ground-based photometry of solar-like stars has led to the suggestion that the solar irradiance may be a factor of 2 to 3 times more stable than stars of similar spectral type and activity level. A small sample (35) of solar-type stars common to the Mt. Wilson HK sample have been monitored photometrically for as long as 30 years at Lowell Observatory (Lockwood, Skiff, & Radick 1997; Radick et al. 1998). The precision of the observations is limited by scintillation noise which is typically at the 1-3 milli-magnitude level. Solar irradiance variations would not be detectable at this precision. Yet only 8 stars in the Lowell sample are "constant" at the mill-mag level both on night-to-night and yearly timescales.

Additional photometric monitoring campaigns have been underway which focus on the stars with planets identified by radial velocity surveys (Henry et al. 1997; Baliunas et al. 1997; Henry et al. 2000). Similar precision – limited by scintillation noise – is achieved (1.1-1.5 mmag). A total of 8 stars have been monitored over a period of 2 to 6 years. The sampling rate is higher than that of the Lowell survey in order to search for transit events in potentially edge-on systems. The authors find that seasonal standard deviations are near the expected limits of precision, suggesting there is no measurable short-term variability in any of the target stars. Although an observational bias (targets were selected by the radial velocity survey for their low levels of magnetic activity) precludes us from drawing any conclusions concerning the statistics of photometric variability among solar-type stars, we can at least conclude that the photometric stability of the Sun is not an isolated case.

Although significant work has been done to photometrically monitor sun-like stars, we have not yet achieved the precision, the temporal resolution, nor the statistical sample necessary to form a complete picture of the variability of solar-type stars. We turn, then, to more theoretical arguments to determine the numbers of stars expected to be sufficiently quiet for photometric detection of terrestrial-sized planets.

4. Rotation, Activity, and Age

The parameter most relevant to the feasibility of planet detection is the stellar rotational period. Convective pro-

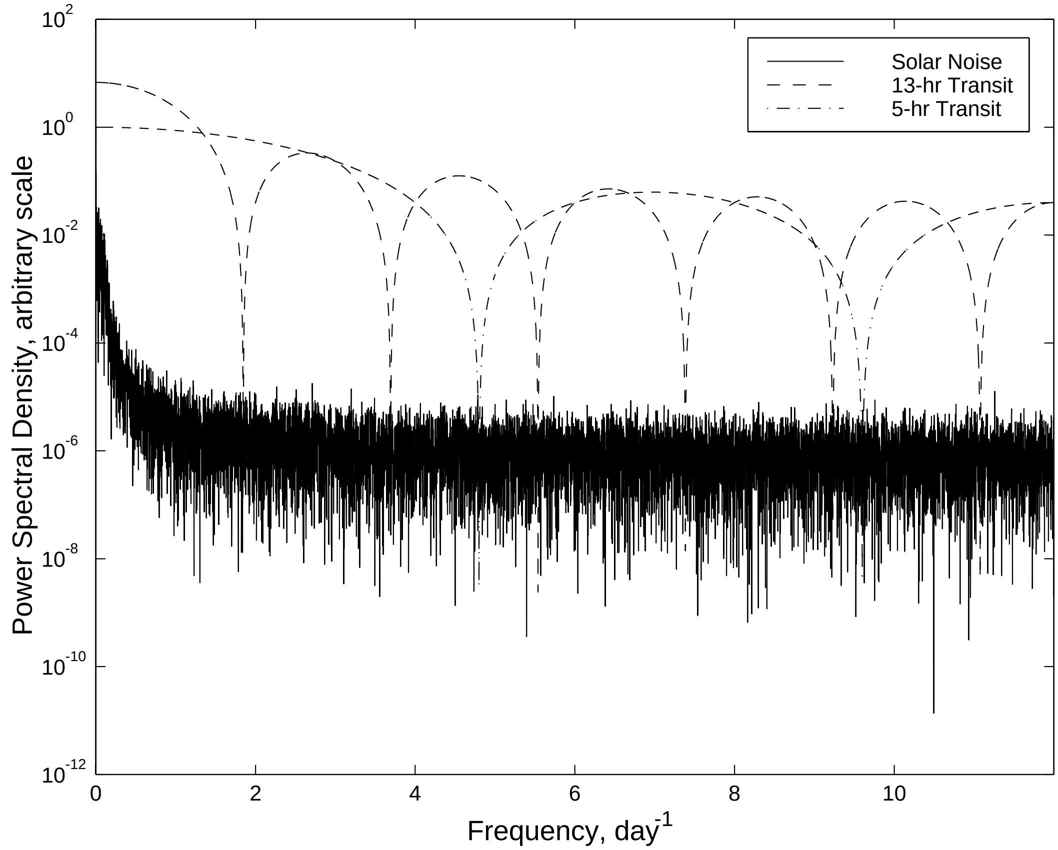

Figure 2. Power Spectral Density of the SOHO/DIARAD data (beginning in 1996). Overplotted for comparison are the PSD's of 5-hour and 13-hour transits. Most of the power in the solar variability occurs at frequencies below 0.1 day^{-1} (or timescales greater that 10 days).

cesses, largely responsible for the variability seen in the Sun on transit time scales, are expected to be similar among stars of a given mass and age. Magnetic processes, however, depend not only on the stellar mass, but also on the stellar rotation rate. In the case of the Sun, magnetic processes appear in the power spectrum primarily at the rotational timescale. Planetary transits occur over very well-defined (and short) timescales. Keeping the rotational timescale (and PSD envelope) far from the transit timescale increases our detection statistics. For this reason, we are interested in estimating the number of sufficiently slow rotators in the *Kepler* sample. Slow rotators are doubly attractive since magnetic processes (and, hence, variability) diminish in the absence of rotation (Catalano & Marilli 1983; Noyes et al. 1984).

To determine how slow is "sufficiently slow", we use the solar irradiance data to test the consequences of increasing both the amplitude of variations as well as the solar rotation rate. Earth-sized transits are detectable up to the point of doubling both the amplitude and the solar rotation rate (decreasing P_{rot} to approximately 15 days). A full description of this analysis will be presented in Jenkins et al. (in preparation). We select a rotational period of 20 days as a conservative estimate of a lower limit and then ask what percentage of dwarfs in the magnitude-limited Kepler field-of-view are expected to rotate at or below this rate (periods of 20 days or longer).

We make use of the age-rotation relation (Kawaler 1989), in conjunction with galactic models publicly available from the Observatoire de Besançon. After a rapid braking phase lasting approximately 0.5 Gy, the rotation rates of late-type stars settle into a distribution typified by open clusters of age equal to or greater than that of the Hyades (700 Myr; Radick et al. 1987). After this phase, rotation rates follow the well-known Skumanich (rotation $\sim \tau^{-0.5}$) empirical spin-down law. The loss of stellar angular momentum is well-modeled as a consequence of the interaction between dynamo-generated magnetic fields and the expanding stellar winds common to late-type stars. Kawaler (1989) derives the dependence of rotational period on age and spectral type:

$$\log(P_d) = 0.5 \log(t_9) + 0.390(B - V) + 0.824$$

where P_d is the rotational period measured in days and t_9 is the stellar age in billions of years. Magnetic spin-down is more efficient in the later-type stars: stars cooler than the Sun will spin down to 20 day rotation periods in 1-3

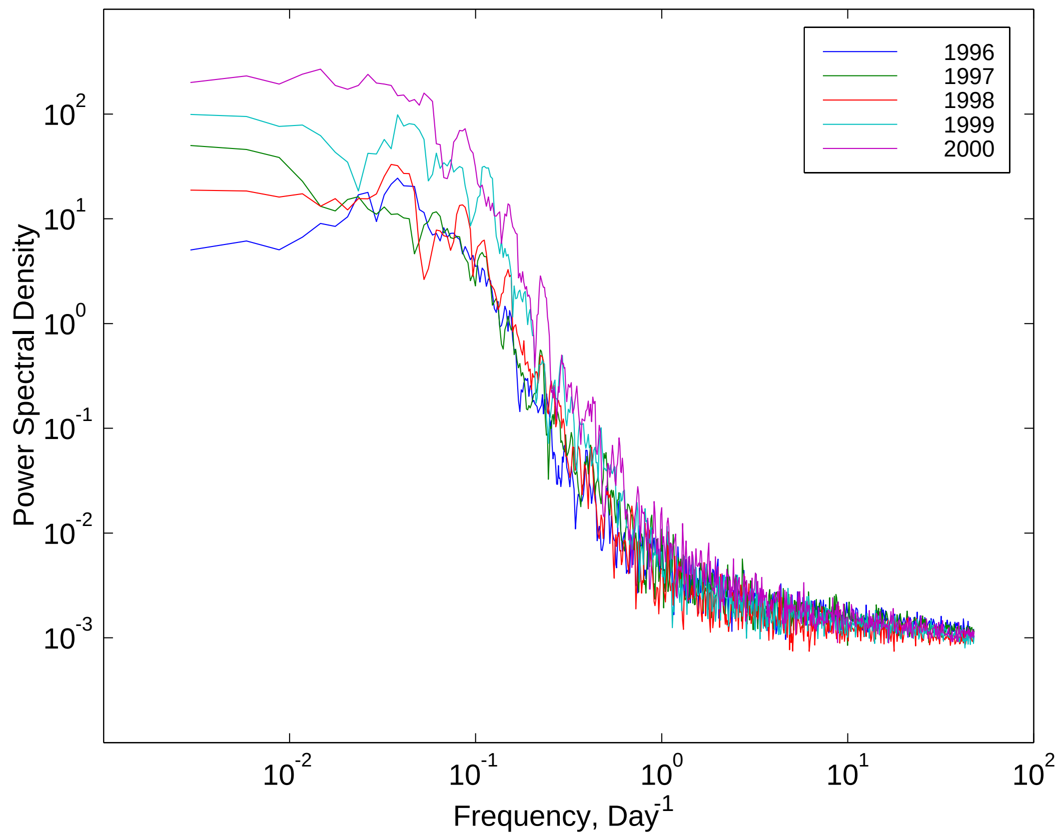

Figure 3. Power Spectral Densities are computed for year-long segments of the SOHO/DIARAD data in order to illustrate the changes in amplitude going from the solar activity minimum of 1996 to the current solar activity maximum. Such changes are significant at the rotational timescale though negligible on timescales relevant to photometric planet detection.

Gyr while middle F-type main sequence stars might take as long as 4.0 Gyr according to the Kawaler models.

The Besançon stellar population models yield estimates of the number of dwarfs in a given spectral-type bin older than the ages derived from the Kawaler formulation. The models are customized to the Kepler field of view and expected magnitude sensitivity. Stars earlier than F7 do not spin down sufficiently before leaving the Main Sequence. And stars later than K9 are too faint (and thus too few) to contribute significantly to the statistics. The exact percentage of stars which will be slowly rotating is a strong function of spectral type and ranges from 40% to 80%. Combining all totals, we find that approximately 65% of F7-K9 dwarfs in the Kepler field are expected to rotate with periods longer than 20 days. This is consistent with CaII H&K surveys of solar-type stars which find that 30-35% of their samples have activity indices above the maximum level observed for the Sun (Henry et al. 1996). It therefore seems assured, on both theoretical and observational grounds, that about two-thirds or more of the solar-type dwarfs in the Kepler field will allow the detection of Earth-like transits. This fraction goes up rapidly as one considers planets only a little larger than the Earth.

5. Summary

White gaussian noise is added to the SOHO/DIARAD solar irradiance data to simulate the expected shot noise and instrumental noise for an $m_V = 12$ star as observed by *Kepler*. Artificial transit events are injected into the data in order to derive the detection statistics in a solar-like noise environment. We find a mean SNR of $\sim 5\sigma$ for 13-hour transits, well above the requirement of 3.5σ for a minimal detection rate of 50%.

Having established the feasibility of Earth-sized transit detection in a solar noise environment, we then look toward existing observations to determine how common sun-like variability is among late-type stars. We find that published data lacks the time resolution, the precision, and the numbers (sample size) necessary to assess the feasibility of Earth-sized transit detection. However, the ground-based photometry of G. Henry and collaborators, focusing on the inactive stars known to have planetary-mass companions, shows these targets are photometrically stable down to their limiting precision of approximately 1 mmag per single observation. This strongly suggests that the very small level of variability shown on the Sun is not an isolated or rare case.

Using the age-rotation relation formulated by Kawaler (1989), we can estimate the age at which solar-type stars spin down to sufficiently slow rotation rates to make planet detection feasible. We define this threshold to be $P_{rot} \sim$ 20 days after simulating the effects of more rapid rotation using the SOHO/DIARAD solar irradiance data. At the slower rotation rates, the amplitude of variations decreases (rotation-activity relation) and the power in the PSD of photometric time series moves away from the transit timescales toward lower frequencies.

Establishing the age at which stars spin down to ~ 20 days as a function of spectral type, we then use the Besançon stellar populations models to compute the numbers of stars in each spectral type bin older than the predetermined age in the Kepler field of view. The Kepler field of view has a pre-defined galactic latitude/longitude and area (100 square degrees). It is limited to stars brighter than $m_V \sim 14$. We find that 40%-80% (depending on spectral type) of main sequence stars in the field have the requisite age. Integrating the results over the all F7-K9 main sequence stars yields 65%.

Not only are detections of Earth-sized planets feasible, they are expected in large numbers (as many as 50, assuming all solar-type stars have two terrestrial-sized planets). Stellar variability is not expected to compromise the science objectives of *Kepler*. Finally, we emphasize that the statistics improve significantly and the number of expected detections rises rapidly when we consider planets even slightly larger than the Earth.

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